The AGE-PRO ALMA Survey: A glimpse into the evolution of gas in protoplanetary disks

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Gobierno de Chile

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AGE-PRO motivation

- Gas is the dominant mass constituent of protoplanetary disks
- Gas impact every major step of planet formation: planetesimal formation, accretion of planetary atmospheres, and migration of planets.

How the gas disk evolves and what mechanism drives the global evolution?

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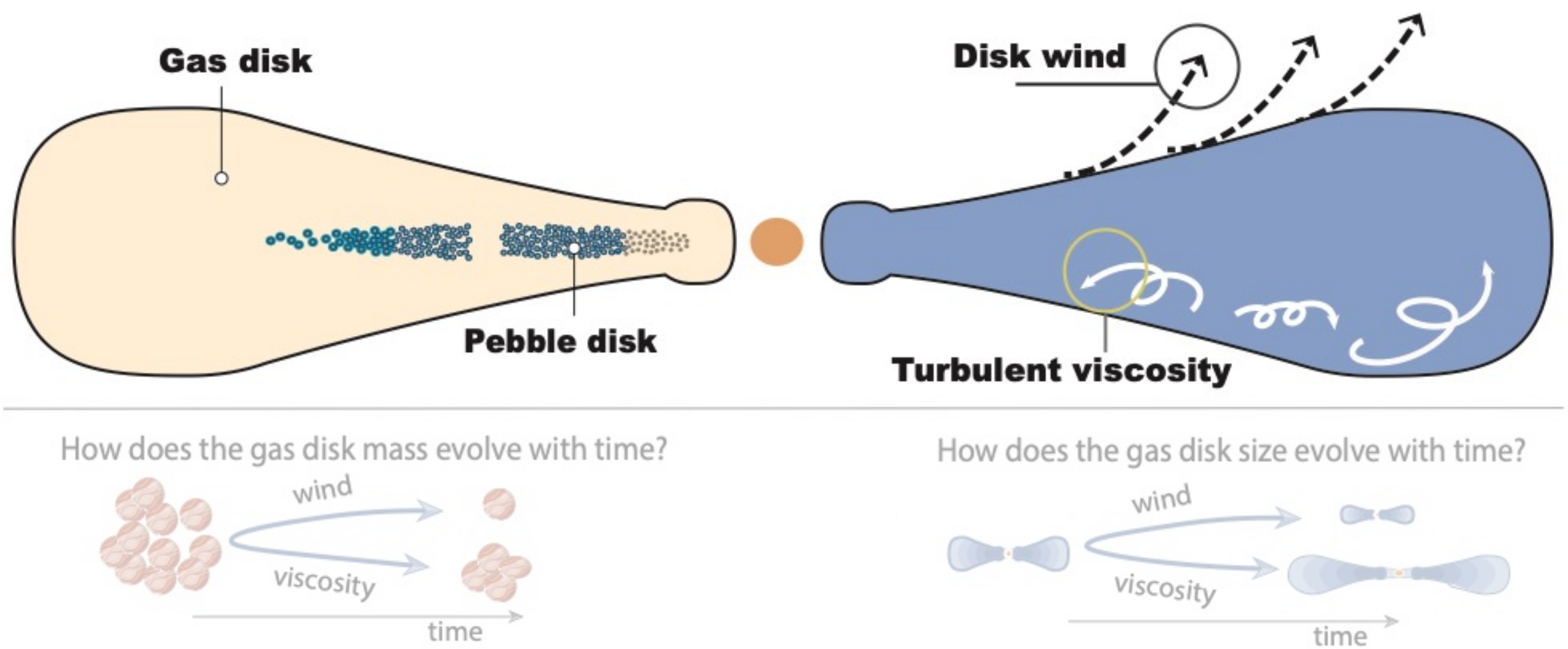

A **wind-driven disk** loses angular momentum as a small amount of gas escapes from the disk surface by traveling along magnetic field lines and gaining angular momentum via magnetic acceleration (e.g., Bai & Stone, 2013).

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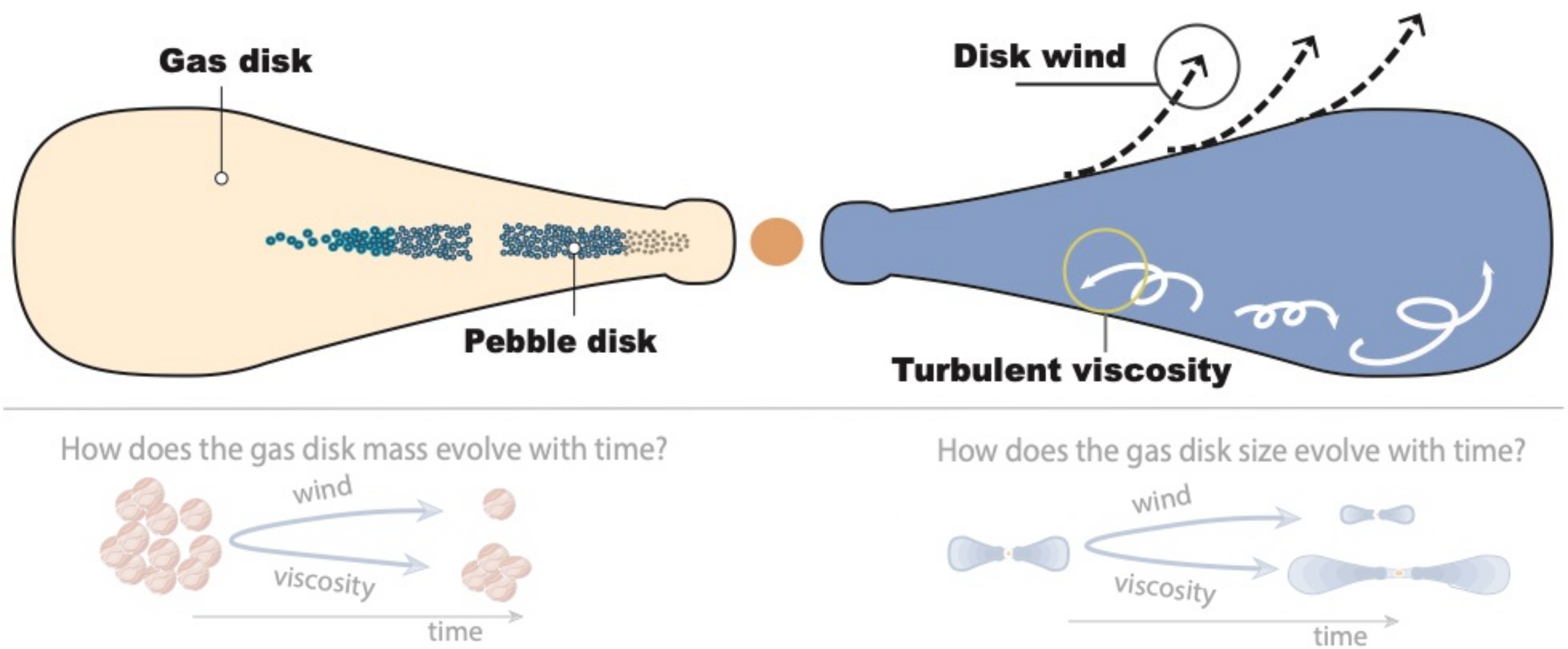
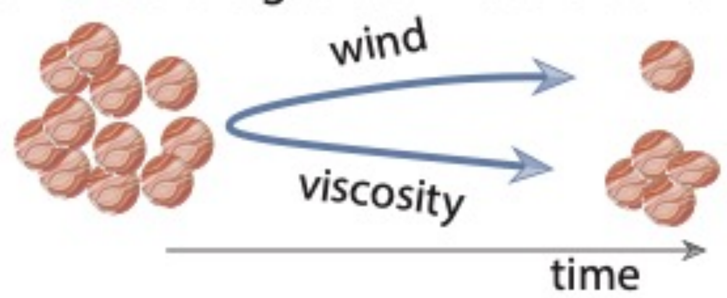


In a **viscous disk**, most of the gas mass loses angular momentum and spirals toward the star, while a small fraction of the gas mass gains angular momentum and moves outward (e.g., Pringle, 1981). As a result, **a viscous disk expands over time.**

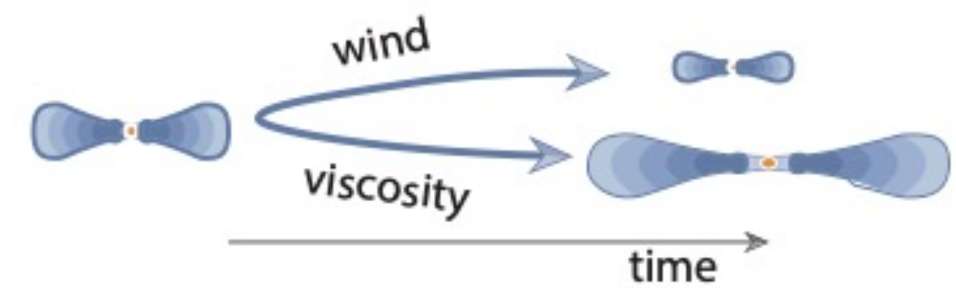
AGE-PRO motivation

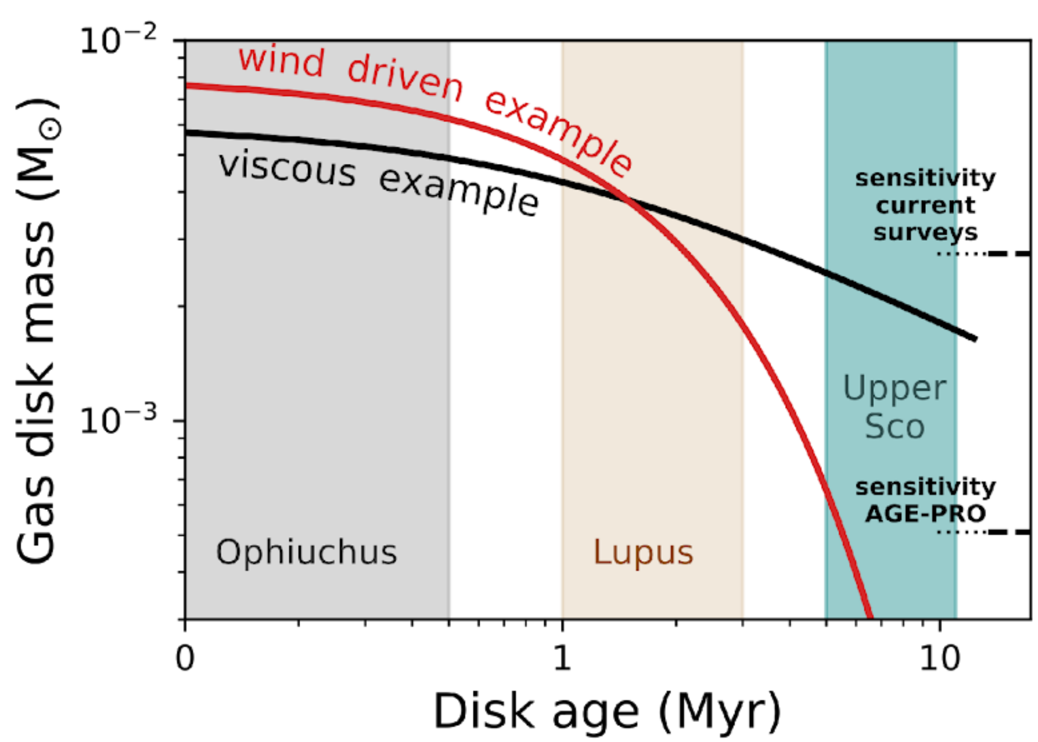
Current disk evolution models predict **distinctive trends** on how the gas disk mass and size evolve, which will be directly tested by this ALMA large program.

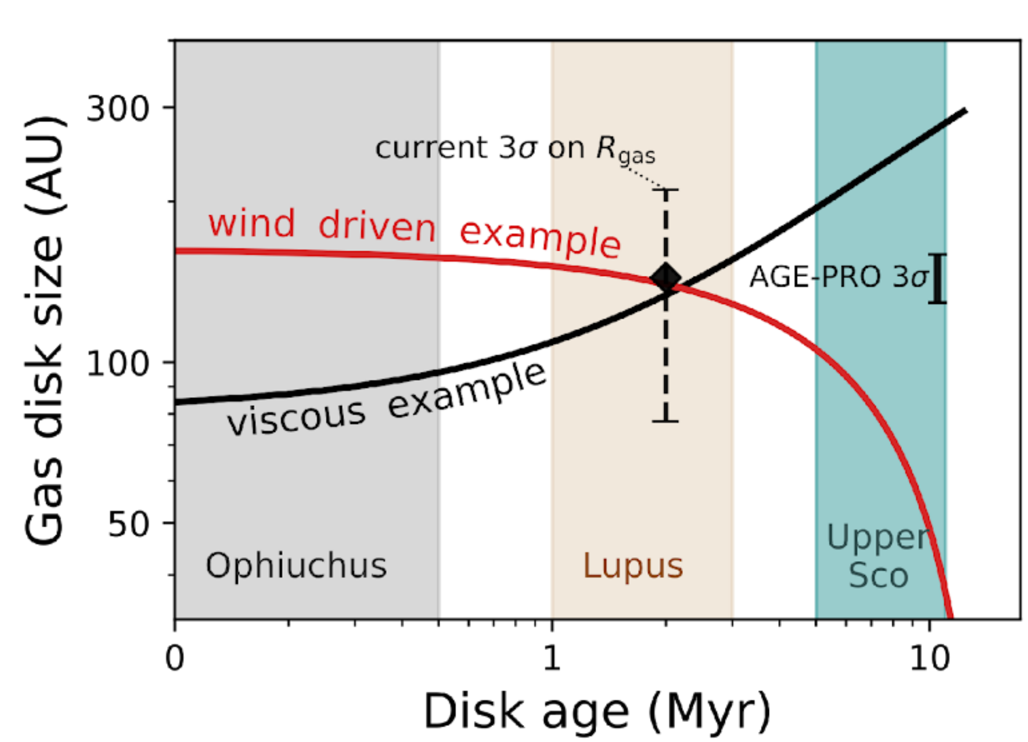
How does the gas disk mass evolve with time?



How does the gas disk size evolve with time?

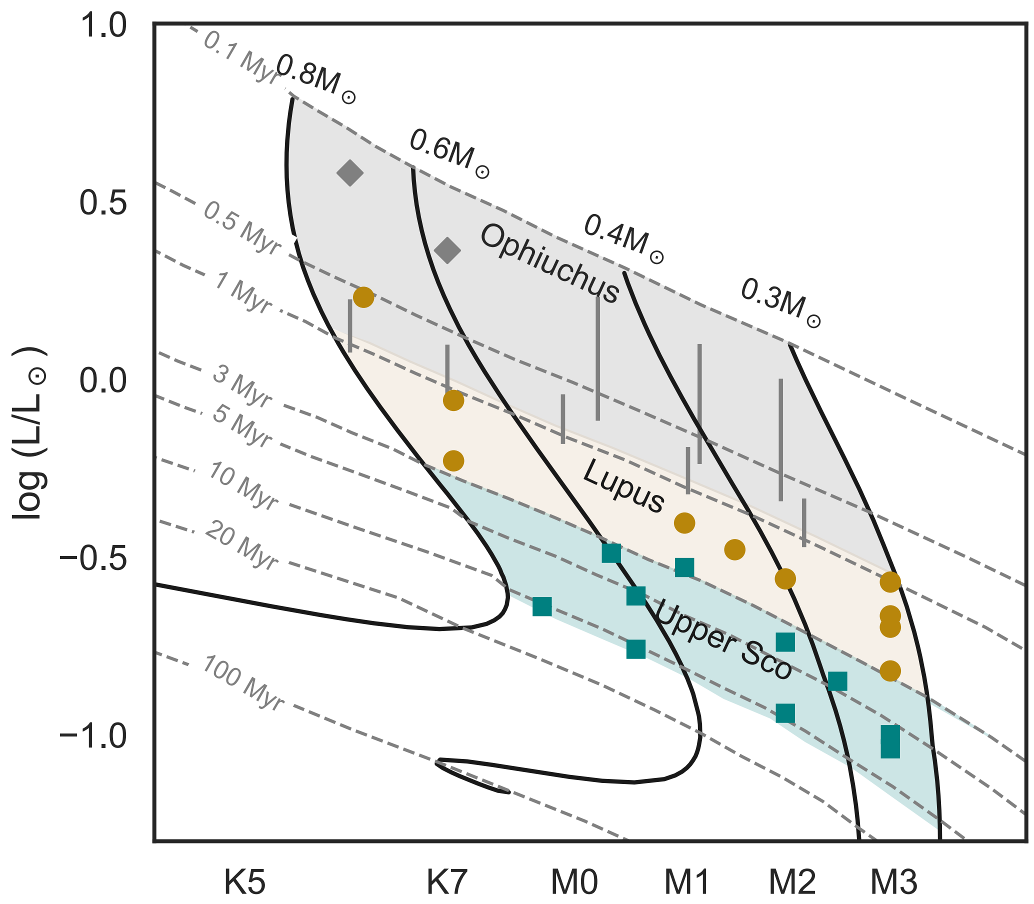


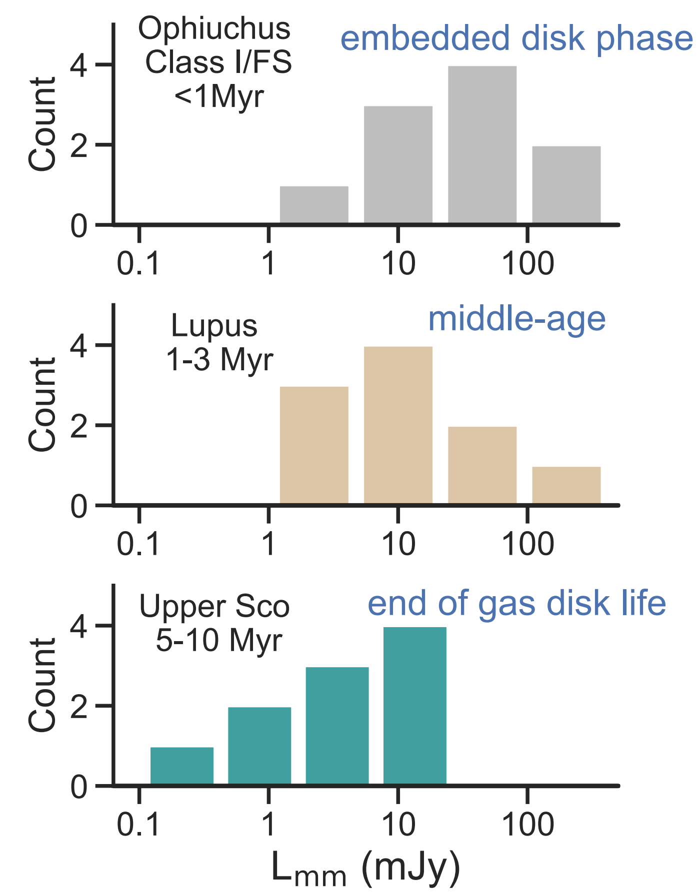




AGE-PRO sample

Our survey covers distinct evolutionary phases: **Ophiuchus (< 1 Myr)** to probe the embedded phase, Lupus (1-3 Myr) to probe the middle-age, and **Upper Sco (5-10 Myr) to probe the end of disk lifetime.**

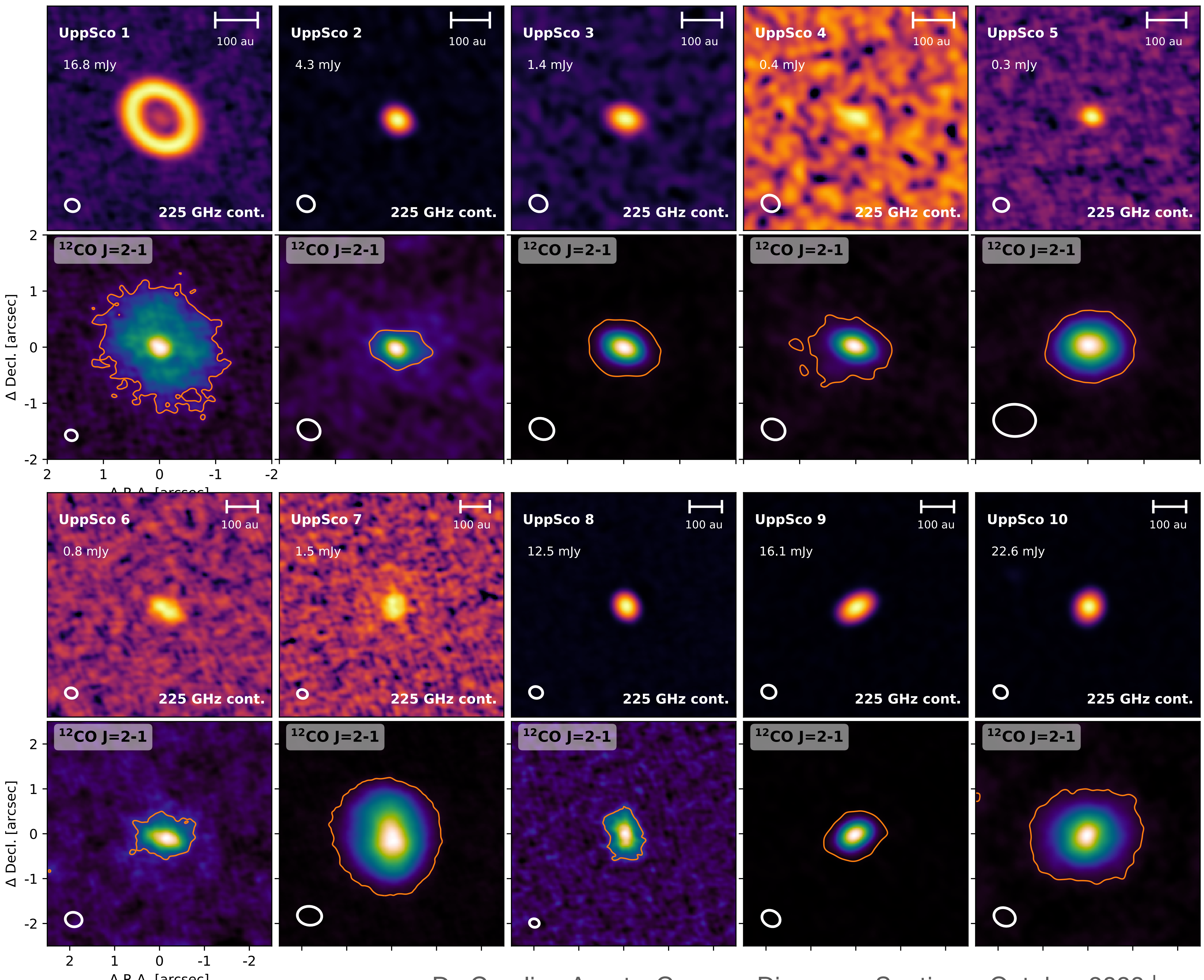




Band	Lines targeted	Beam	Int. time
B6	12CO, 13CO, C18O (2-1), H2CO (3-2), DCN (3-2), N2D+ (3-2)	0.2''	30min
B6	$C^{17}O$ (2-1) .SO_2(6-7), CH_3CN(13-12), SO(1-2), CH_3OH (4-5)	0.2''	1hr
B6	12CO, 13CO, C18O (2-1), H2CO (3-2), DCN (3-2), N2D+ (3-2), CH3CN (12-11)	0.2''	30min
B7	N_2H^+ (3-2), DCN (4-3), $C^{34}S$ (6-5), DCO^+(4-3)	0.6''	1hr
B6	12CO, 13CO, C18O (2-1), H2CO (3-2), DCN (3-2), N2D+ (3-2), CH3CN (12-11)	0.2''	1hr
B7	N2H+ (3-2), DCN (4-3), C34S (6-5), DCO+(4-3)	0.6''	2hr

AGE-PRO ("ALMA survey of Gas Evolution in PROtoplanetary disks") Upper Scorpius:

Measuring key gas disk properties at the end of the disk lifetime



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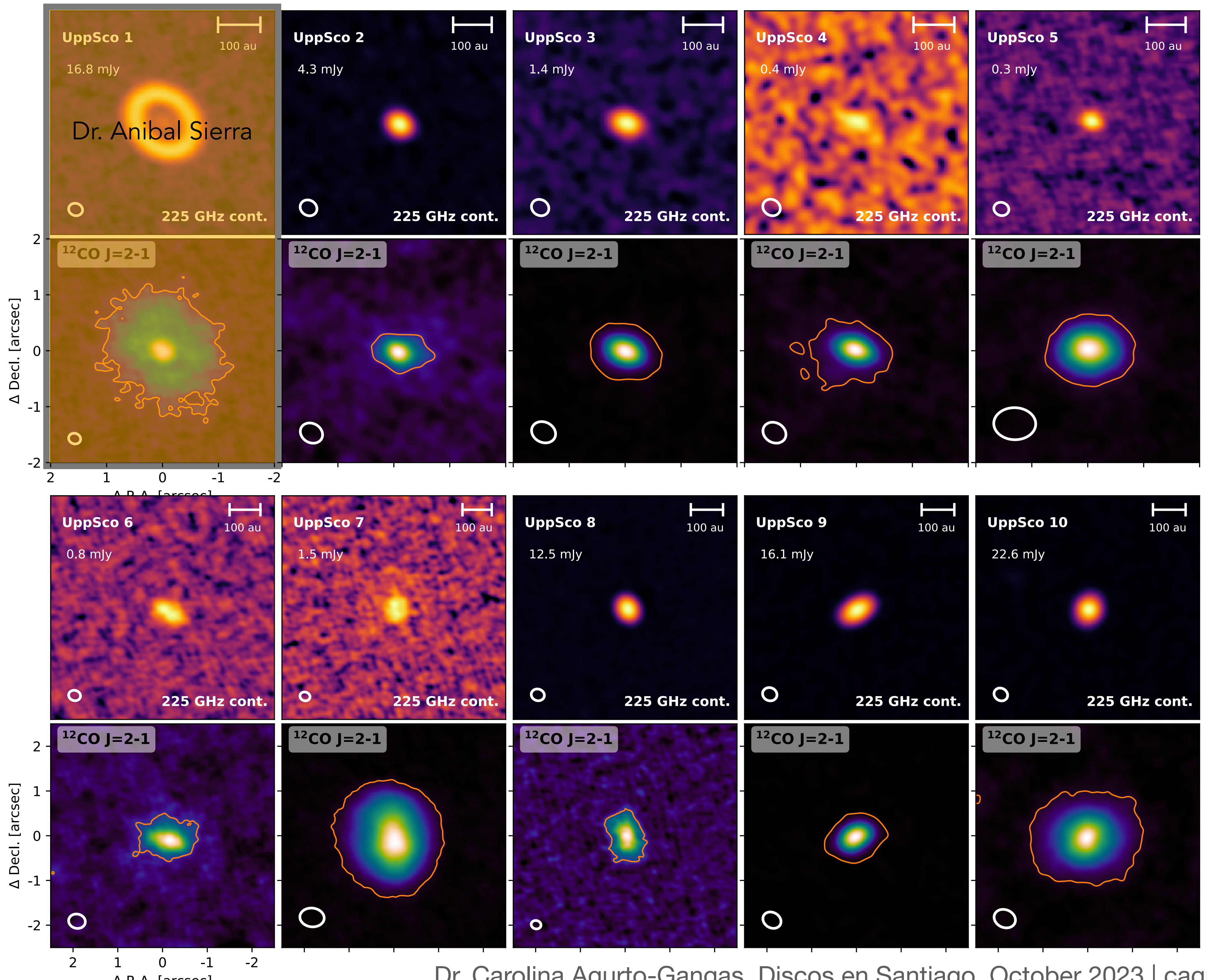

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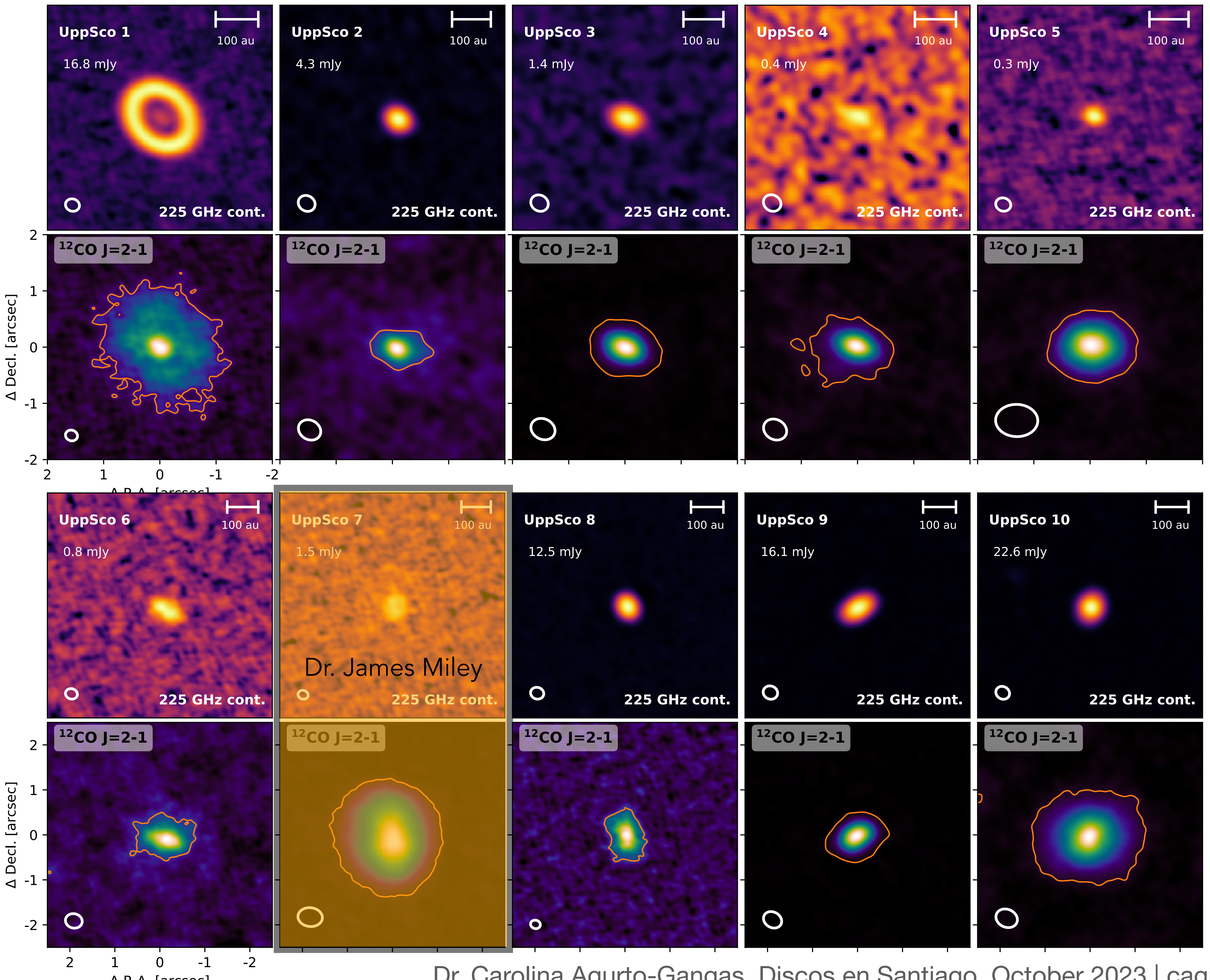

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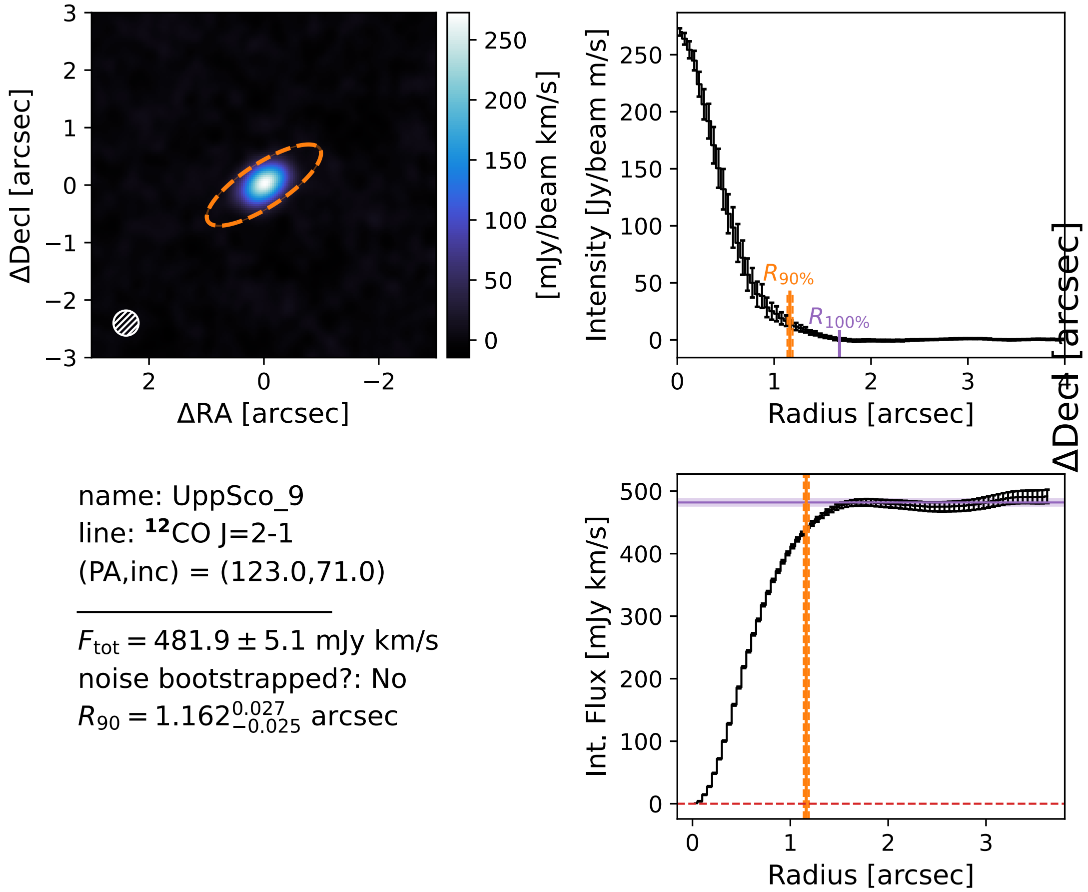
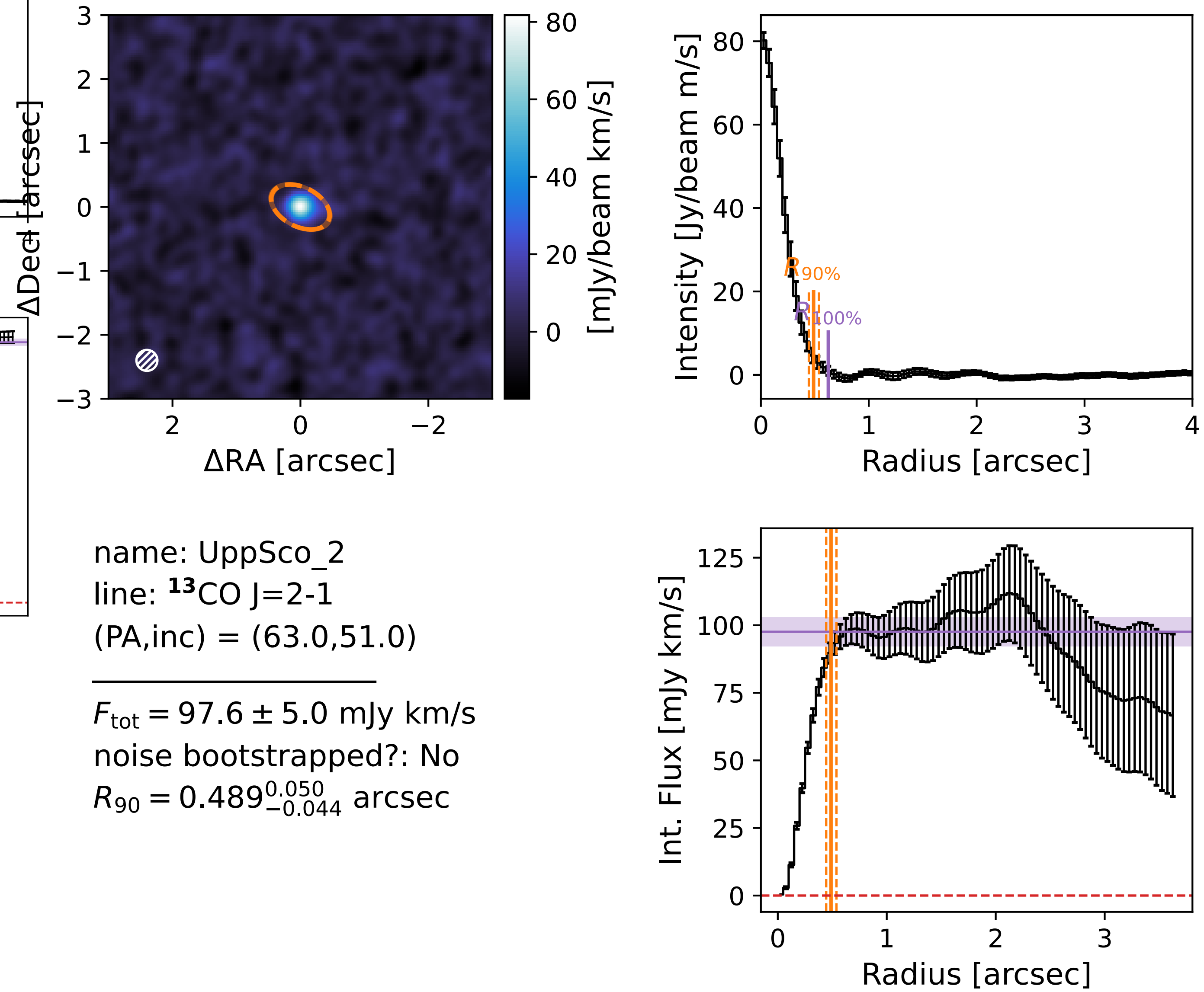


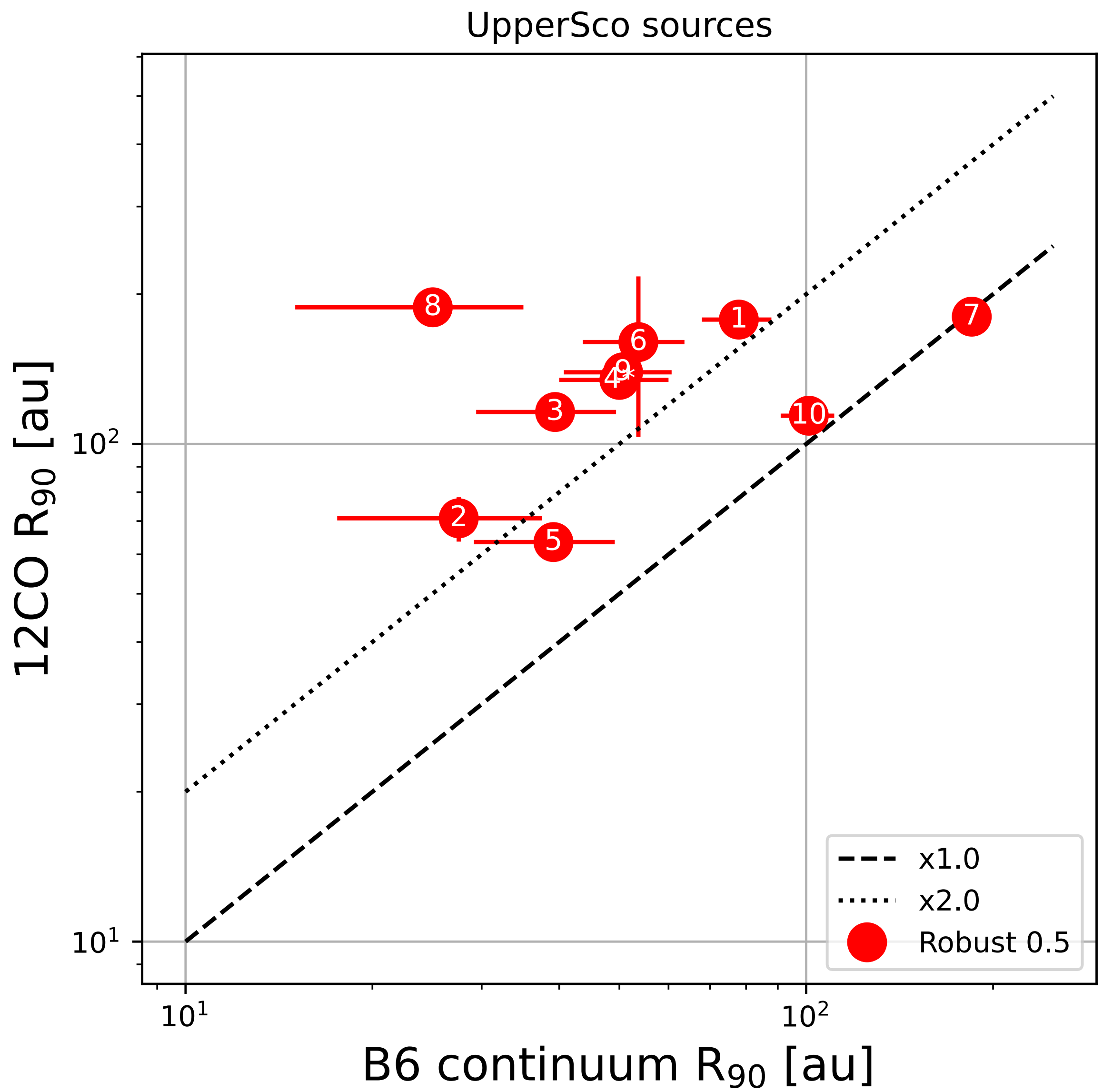
name: UppSco_9
line: ^{12}CO J=2-1
(PA,inc) = (123.0,71.0)

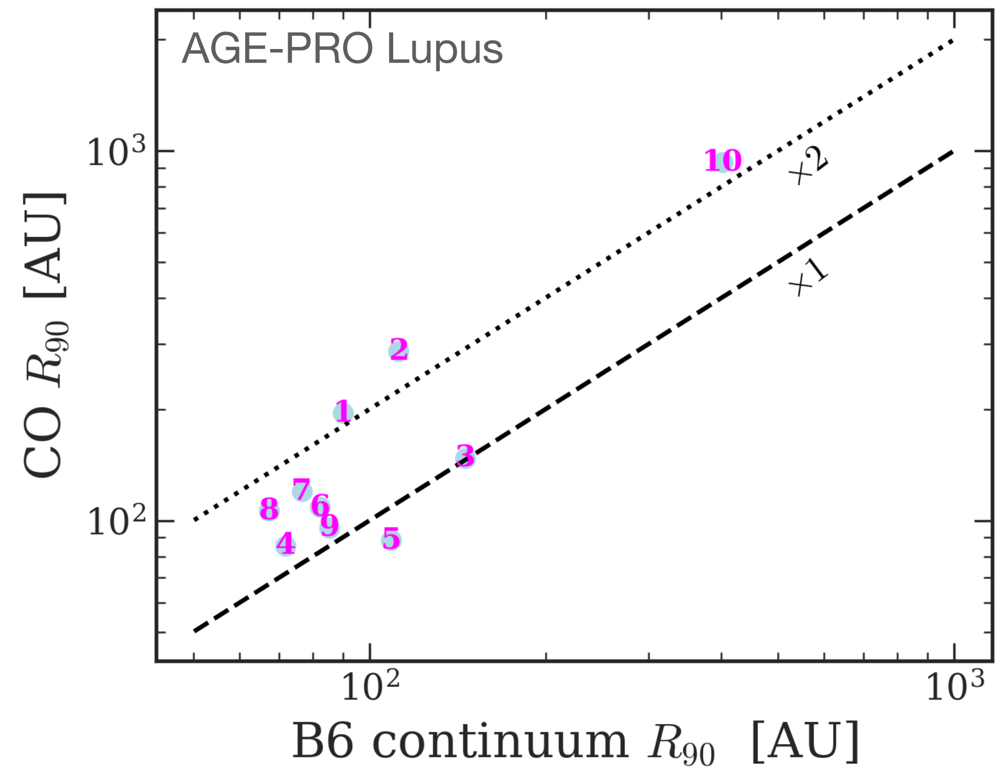
$F_{tot} = 481.9 \pm 5.1$ mJy km/s
noise bootstrapped?: No
$R_{90} = 1.162^{0.027}_{-0.025}$ arcsec

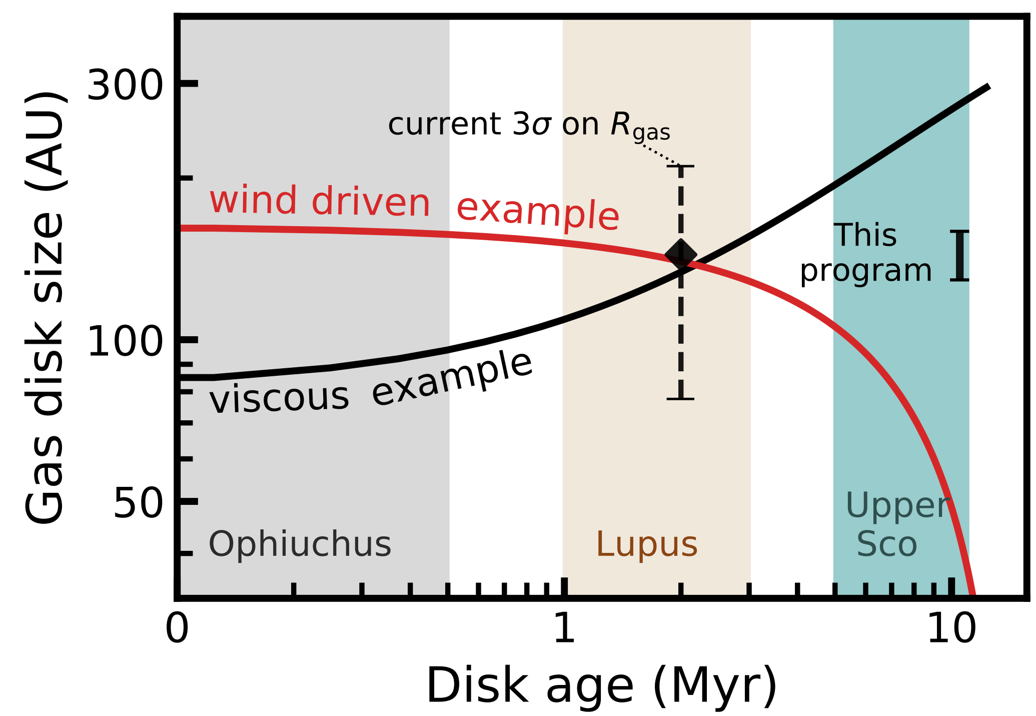


name: UppSco_2
line: ^{13}CO J=2-1
(PA,inc) = (63.0,51.0)

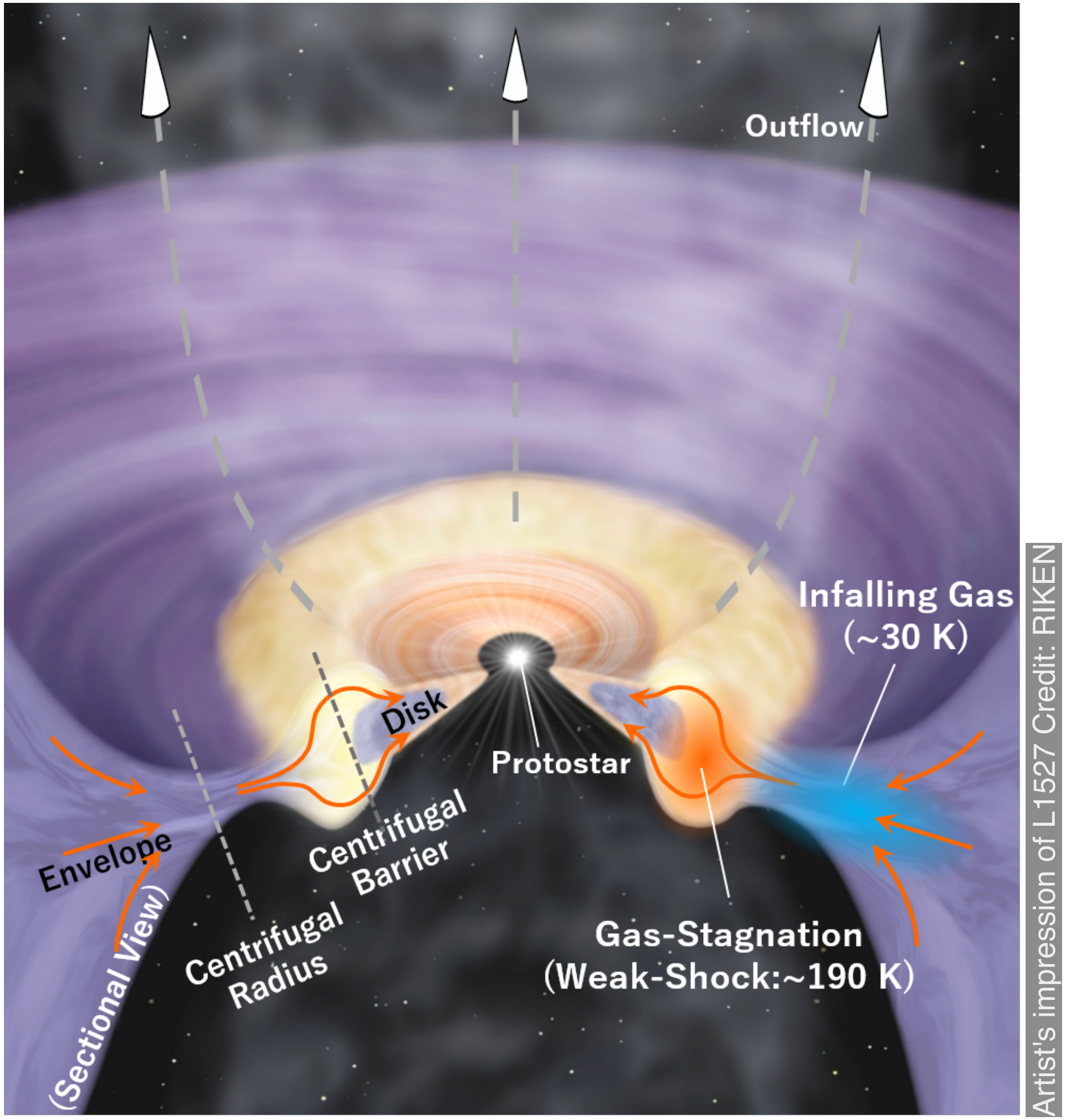
$F_{tot} = 97.6 \pm 5.0$ mJy km/s
noise bootstrapped?: No
$R_{90} = 0.489^{0.050}_{-0.044}$ arcsec


UpperSco sources
12CO R90 [au]
B6 continuum R90 [au]
x1.0
x2.0
Robust 0.5


AGE-PRO Lupus
CO R90 [AU]
B6 continuum R90 [AU]


current 3σ on Rgas
wind driven example
viscous example
This program
Gas disk size (AU)
Disk age (Myr)
Ophiuchus
Lupus
Upper Sco

AGE-PRO. Constraining the physical structure of the **disk-envelope interface** in Ophiuchus using **Position-Velocity (PV) diagrams** of CO isotopologues



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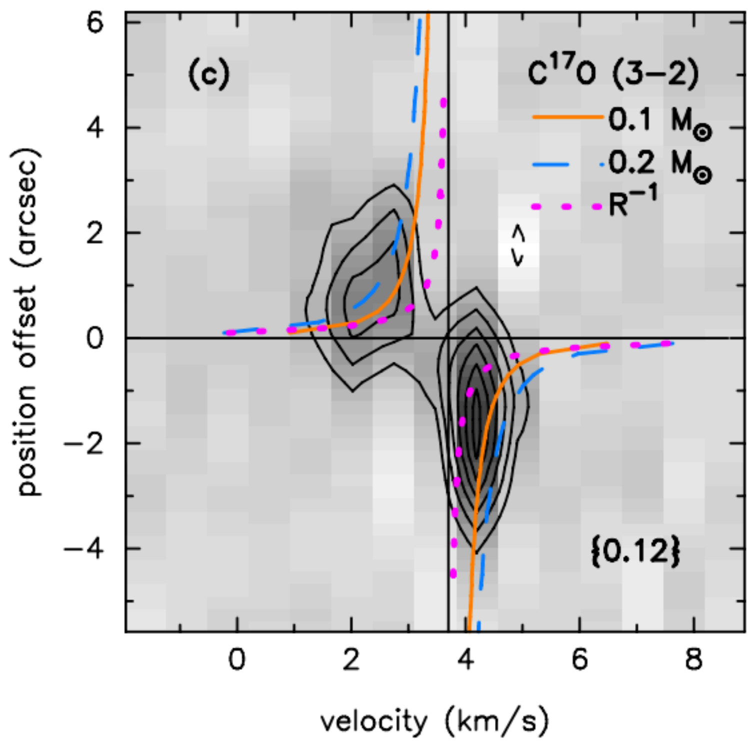
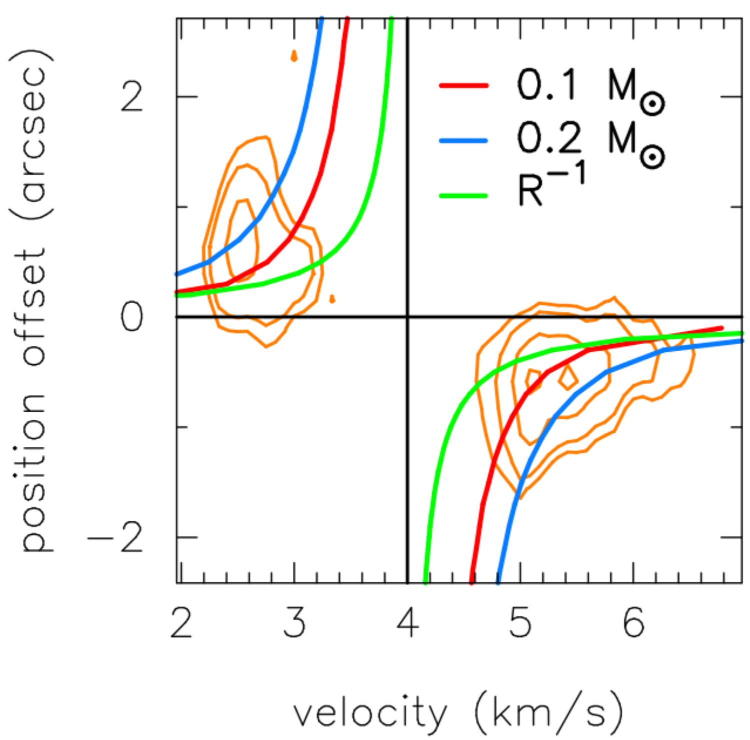
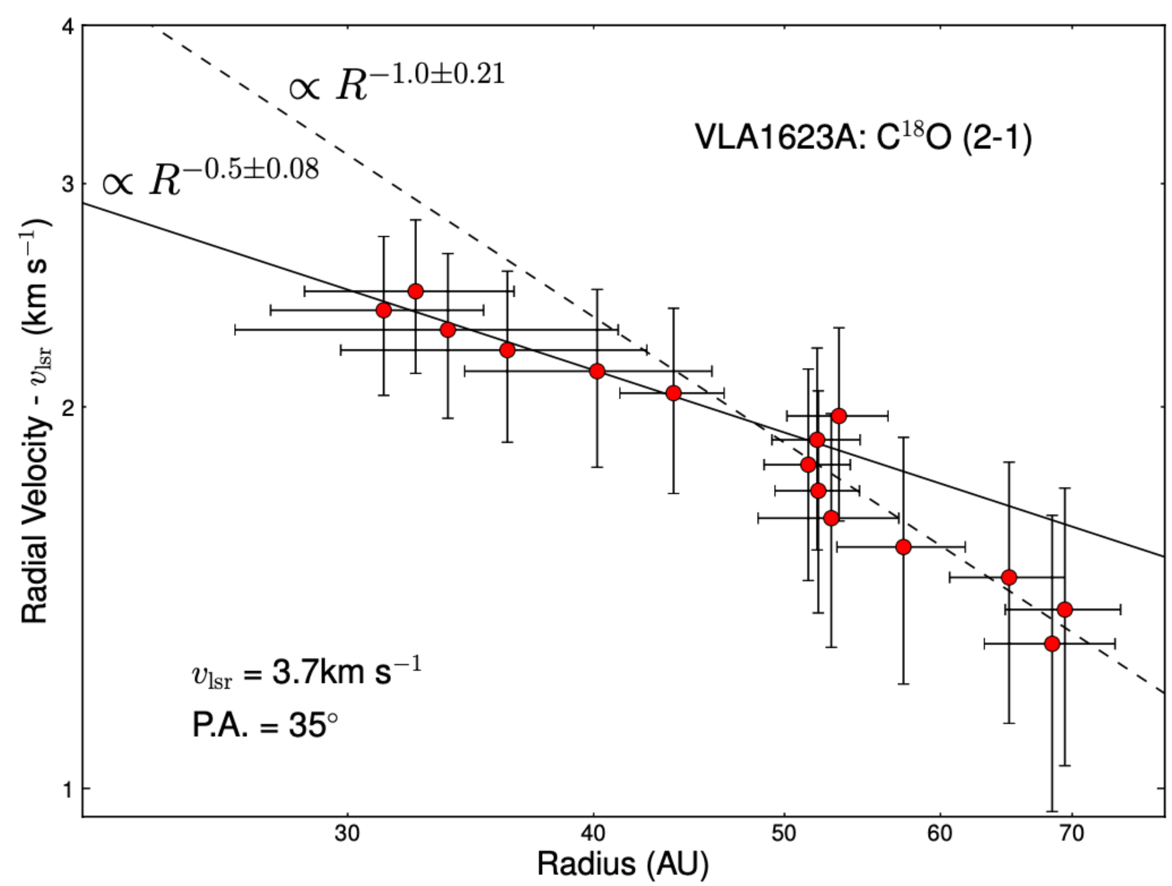
Murillo et al. 2013





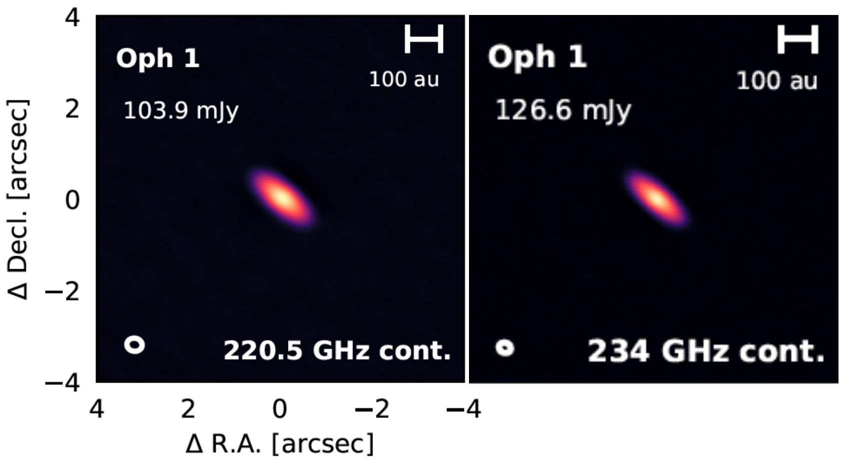
UV-space PV diagrams are **constructed by fitting, channel by channel, the UV visibilities of the line emission to find the peak position in each channe**l (Lommen et al. 2008; Jørgensen et al. 2009).



Pure Keplerian rotation curves (v ∝ R −0.5 , red and blue) and infall (v ∝ R −1 , green) are overlaid on the PV diagram.

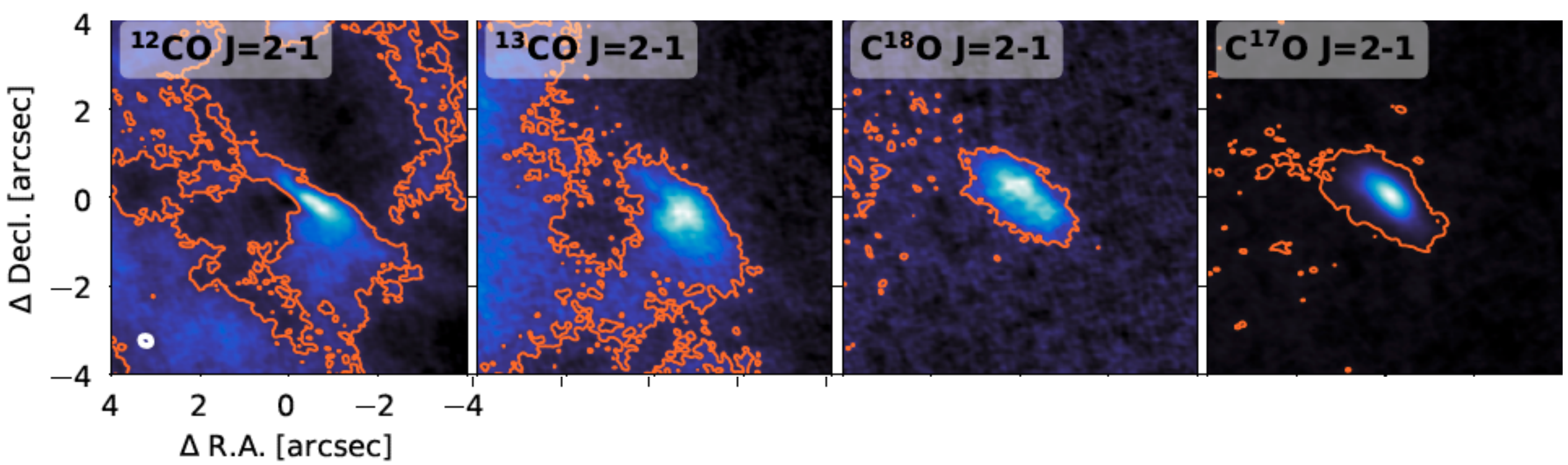
AGE-PRO. Constraining the physical structure of the **disk-envelope interface** in Ophiuchus using **Position-Velocity (PV) diagrams** of CO isotopologues

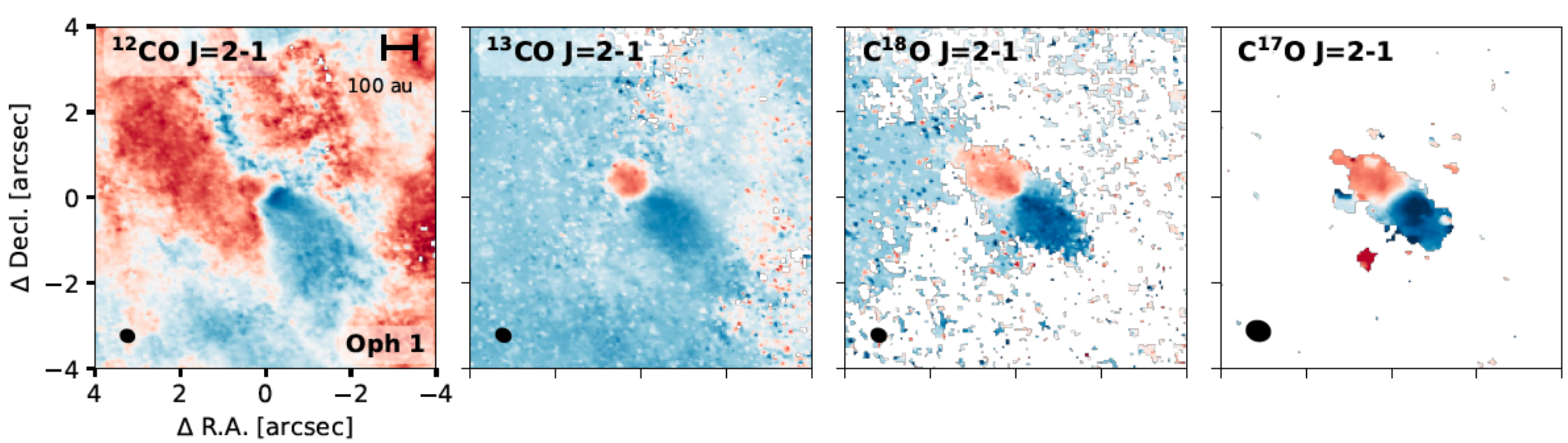
Oph_1_SSTc2d_J162623.6-242439



SLAM: Spectral Line Analysis/Modeling

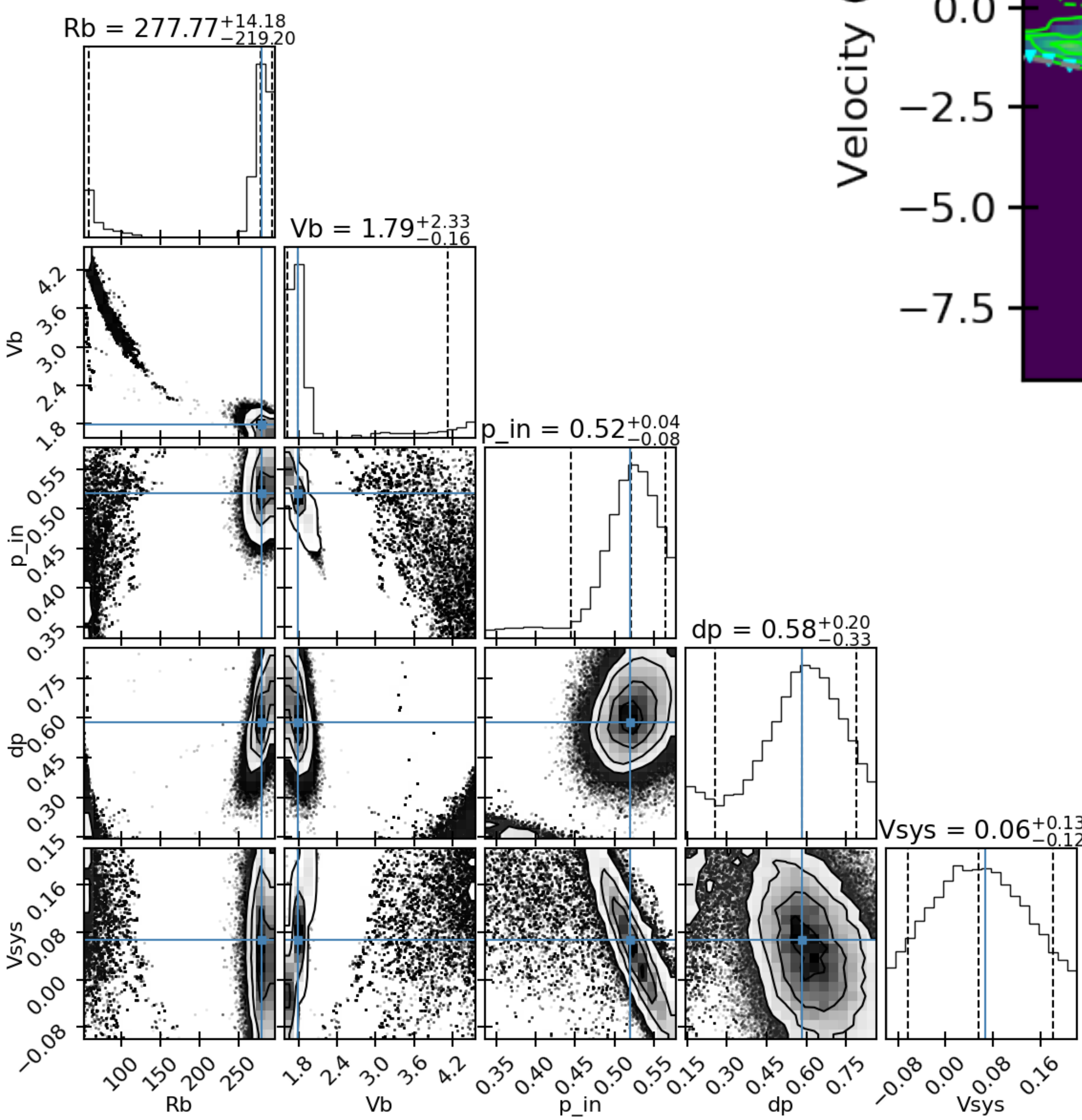
SLAM (Spectral Line Analysis/Modeling) is a python library to analyze/model spectral line data especially obtained with radio telescopes. The current main package, pvanalysis, is to derive the rotational velocity as a function of radius and fit the profile with a power-law function. The detail of the method is presented in Aso et al. 2015, Sai et al. 2020 and the reference therein. More analysis tools will be coming in future.

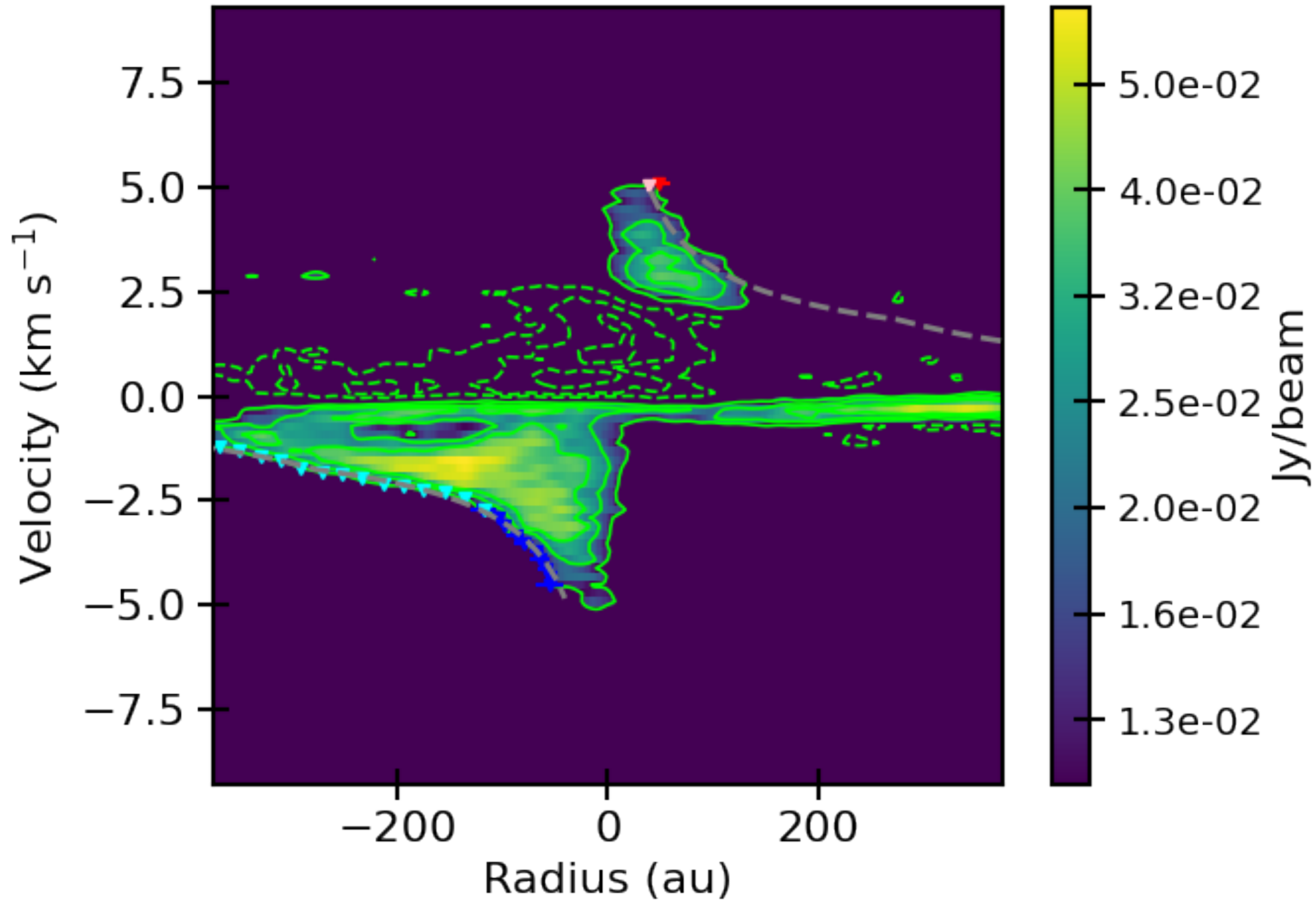




The moment 1 map was created over the same velocity range as the moment 0 map, with the emission having an intensity of more than 3σ

C17O






```
--- Edge ---
R_b    = 277.77 +/- 116.69 au
V_b    = 1.793 +/- 1.243 km/s
p_in   = 0.522 +/- 0.060
dp     = 0.584 +/- 0.265
v_sys  = 2.356 +/- 0.122
r      = 38.22 --- 447.58 au
v      = 1.114 --- 5.100 km/s
M_in   = 1.199 +/- 1.695 Msun
M_out  = 0.617 +/- 1.000 Msun
M_b    = 1.100 +/- 1.594 Msun
```

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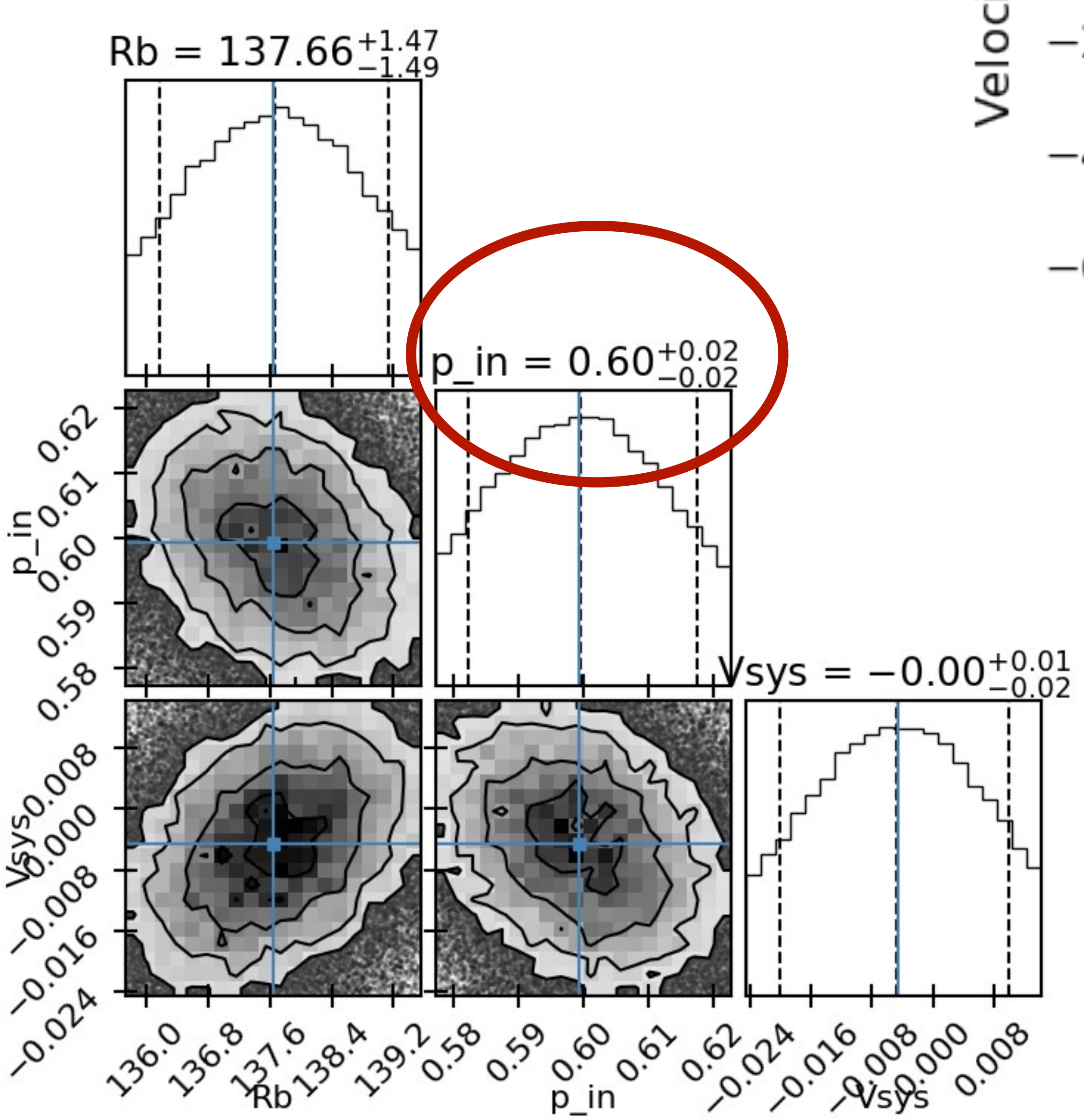
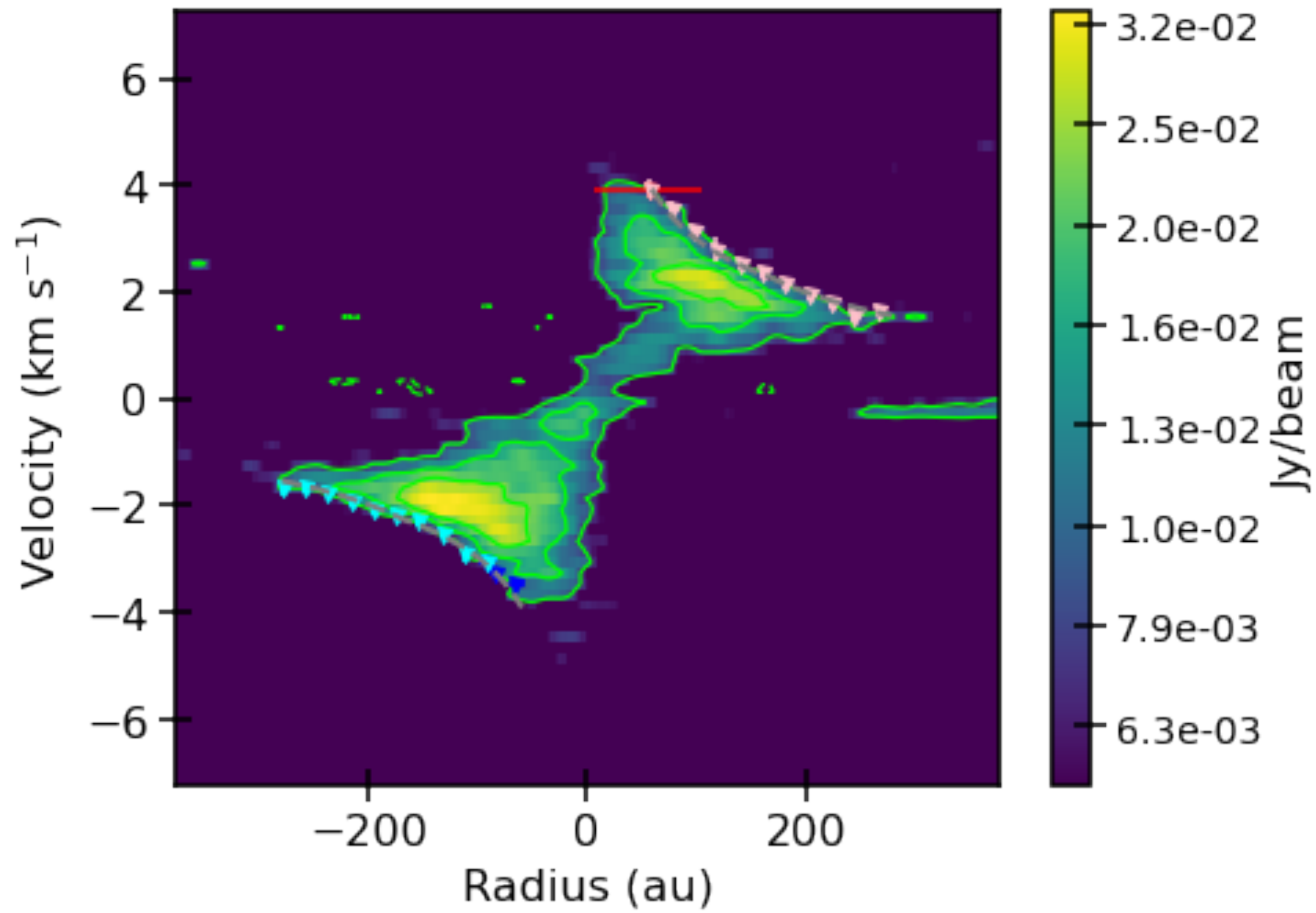
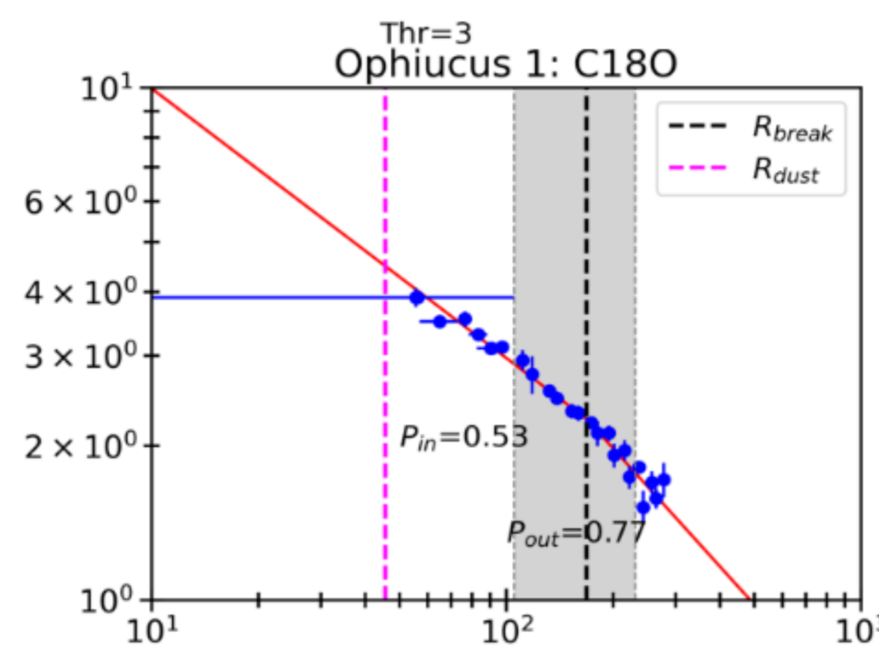
C18O

```
--- Edge ---
R_b   = 137.66 +/- 1.48 au
V_b   = 2.337 +/- 0.000 km/s
p_in  = 0.600 +/- 0.018
dp    = 0.000 +/- 0.000
v_sys = 2.295 +/- 0.015
r     = 58.47 --- 258.54 au
v     = 1.596 --- 3.900 km/s
M_in  = 1.099 +/- 0.031 Msun
M_out = 0.817 +/- 0.026 Msun
M_b   = 0.926 +/- 0.010 Msun
```







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Preliminary results

Source	Molecule	Rbreak	Rbreak_error	V_break	Vbreak_error	Pin	Pin_error	Pout	Pout_error	Min	Min_error	Mout	Mout_error
		au	au	km/s	km/s	(0.5 keplerian)		(1.0 infall)		Msun	Msun	Msun	Msun
Oph1	13CO	249.44	19.22	2.039	0.192	0.5	0.045	0.99	0.127	1.308	0.347	0.762	0.259
Oph1	C17O	157.87	8.59	2.607	0.107	0.47	0.053	1.10	0.173	1.603	0.180	0.927	0.154
Oph1	C18O	168.18	62.96	2.259	0.545	0.52	0.067	0.77	0.191	1.143	0.694	0.829	0.655
Oph2	12CO	193.17	4.32	2.565	0.058	0.284	0.016	1.71	0.228	0.723	0.092	0.719	0.122
Oph2	13CO	114.75	41.01	2.321	0.0545	0.495	0.067	0.75	0.595	0.715	0.432	0.618	0.130
Oph3	12CO	206.71	14.13	1.193	0.103	0.5	nan	1.87	0.622	0.43	0.092	0.179	0.130
Oph3	13CO	64.41	15.74	2.392	0.294	0.363	0.105	0.62	0.150	0.475	0.211	0.427	0.215
Oph7													
Oph8	12CO	61.69	9.60	4.701	0.2	0.22	0.016	0.53	0.128	0.85	0.228	1.689	0.422
Oph9	12CO	144.49	62.98	3.141	1.374	0.52	0.130	0.83	0.970	1.789	1.829	1.447	1.628
Oph9	13CO	94.13	6.52	3.762	0.164	0.5	nan	1.80	2.616	1.569	0.180	1.439	0.416
Oph9	C18O	48.01	13.85	4.968	0.982	0.5	0.356	0.91	0.396	1.396	0.663	0.955	0.702
Oph10	12CO	58.02	9.74	2.297	0.623	0.5	nan	0.94	0.420	0.582	0.308	0.236	0.276

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Final remarks

Products to the community

1. Self-calibrated and imaged data cubes of targeted lines and continuum images of all disks, and standardized scripts that reproduce the image cubes from the calibrated data delivered by ALMA.
2. Extracted spectra, moment 0 maps using Keplerian masks, and radial profiles of all targeted lines and disks, together with the scripts used to reproduce these high-level data products.

Science goals

Constrain global disk evolution mechanisms by comparing model predictions with mass and size measurements of disks at different ages.

The results will establish a baseline understanding of the global structure and evolution of protoplanetary disks, providing essential context for future in-depth studies of planet formation processes in disks.

Future follow up surveys !

ALMA: Dust evolution in planet-forming disks: from early stages to the end of disk lifetime

- continuum observations for the full AGE-PRO sample at 2.9 and 1.8 mm

(**see Poster of Camila Pulgares**)

JWST: Title: Building on ALMA: a JWST legacy survey of the chemical evolution of planet-forming disks

- to study the evolution of mid-IR molecular line emission across protoplanetary disk ages.